First Rib Metamorphosis: Its Possible Utility for Human Age-at-Death Estimation

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ABSTRACT Human first ribs demonstrate predictable, sequential changes in shape, size, and texture with increasing age, and thus, can be used as an indicator of age at death. Metamorphosis of the first rib's head, tubercle, and costal face was documented in a cross-sectional sample of preadult and adult first ribs of known age at death from the Hamann-Todd skeletal collection (Cleveland Museum of Natural History, Cleveland, Ohio). Blind tests of the usefulness of the first rib as an age indicator were conducted, including tabulation of intraobserver and interobserver inaccuracies and biases. First rib age estimates show inaccuracies and biases by decade comparable to those generated by other aging techniques. Indeed, the first rib method is useful as an isolated age indicator. When used in conjunction with other age indicators, the first rib improves the quality of summary age assessments. Am J Phys Anthropol 110:303–323, 1999. © 1999 Wiley-Liss, Inc.

The costochondral cartilage of ribs has received considerable attention as a chronological age indicator. Several radiologic and morphologic studies have analyzed ossification patterns of the costochondral cartilage with respect to age (Michelson, 1934; Falconer, 1938; King, 1939; Hass, 1943; Stewart, 1954; Dearden et al., 1974; Semine and Damon, 1975; McCormick, 1980; McCormick and Stewart, 1983, 1988; Kampen et al., 1995; Barchilon, et al., 1996).

İşcan, Loth, and colleagues shifted the focus from ossified sternocostal cartilage to the modeling (remodeling) process of the fourth rib costal face. These authors have described multiple morphologic features of the human fourth rib that have been useful for estimating age-at-death (İşcan et al., 1984, 1987, 1992; İşcan and Loth, 1986a, 1986b; Loth and İşcan, 1994; Loth, 1995). Indeed, the usefulness of the fourth rib in aging skeletal material has been confirmed independently (Russell et al., 1993; Dudar et al., 1993).

Although useful in aging skeletal remains, the fourth rib aging method presents several limitations for the forensic and physical anthropologist, not least of all misidentification in unarticulated skeletons or broken ribs (see also Dudar, 1993). Focus on the costochondral junction does not take advantage of additional changes in the rib which occur throughout life, especially at the head and tubercle. Similarly, calcification of the chondral surfaces of the lower ribs is influ-

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enced by mechanical stress (King, 1939; Haines, 1940; Semine and Damon, 1975) and biased by sex and race (Michelson, 1934; McCormick, 1980; McCormick and Stewart, 1983; İşcan and Loth, 1986a,b; İşcan, et al., 1987).

In the present study, an effort has been made to construct an aging method based on first rib metamorphosis that limits the effects of these confounding influences. The first rib offers three qualities that make it a favorable age indicator. First, it is unambiguously identifiable. Second, the bone and its cartilages demonstrate an early onset and lengthy span of remodeling continuing into the eighth decade and beyond. Third, radiographic studies of the ossification of the rib cartilage demonstrate that the pattern of ossification in the first rib occurs generally in a costochondral to sternal direction, more so in this rib than in the lower ribs (Nishino, 1969). As such, this study of the first rib and its metamorphosis examines a fundamental and sequential process of osteologic change with age that serves as a new, independent assessment of age at death and one that examines a distinct aging phenomenon not evaluated by other classical techniques. Thus, the aims of the present study are: (1) to construct an aging standard using the first rib for preadult and adult skeletons using the growth and remodeling of the costal face, tubercle, and head; (2) to test the reliability and validity of the proposed method by independent observers; and (3) to evaluate the accuracy of the first rib method compared to a multifactorial, summary age method (using symphysis pubis, auricular surface, cranial suture closure, dental attrition, and trabecular involution of the proximal femur).

MATERIALS AND METHODS

Stage 1: identification of morphologic changes in the first rib

Stage 1 consisted of examining a study sample of first ribs to identify metric and morphologic characteristics of the growth and remodeling of the costal face, tubercle, and head. Specimens were drawn from the Hamann-Todd Osteologic Collection (curated by the Laboratory of Physical Anthropology at the Cleveland Museum of Natural History). This collection has 3,100 well-documented cranial and postcranial human skeletons (known age at death, sex, race, cause of death, height, and weight) (Mensforth and Latimer, 1989; Kern and Latimer, 1997), and comprises a large population of black and white men and women born between the years of 1825 and 1910. For the present study, it is important to note that individuals included in the Hamann-Todd collection were largely indigents of low socioeconomic status. Western Reserve University anatomists accessioned human cadaveric skeletal materials for this osteologic archive between the years of 1910 and 1940; and thus, the human sample used in this study represents a cross section of early 20th century urban industrial America. This population provides the unique opportunity to study the effects of age-related bone change in a diverse urban industrial community prior to the initiation and widespread use of antimicrobial interventions, hormonal replacement therapies, and nutritional and dietary supplementation (Mensforth and Latimer, 1989).

First, to determine a sequence of morphologic change in the first rib, a study sample of 74 age-verified nonpathological preadult and adult first ribs was drawn. Age, sex, and race were known for each specimen in this study sample (Table 1). Indeed, this sample (and all individuals included in this study) consists of individuals in which age at death has been confirmed independently. A “flat” age distribution [mean (SD) = 37.7 (21.7) years, range = 1–75 years] was chosen with approximately equal representations in each decade (Fig. 1). Each rib was seriated according to documented chronological age. In doing so, two markers for biologic age became apparent. First, the absence or presence of secondary centers of ossification at the rib head and tubercle separated preadult specimens from adult specimens. Second, the overall size and shape of the first rib as well as changes in the topography and texture of the costal face, rib head, and tubercle facet identified changes in morphology that paralleled increases in age. Particular attention was paid to the shape, surface

TABLE 1. Sample composition for study, test, and summary age samples

Age groups	Stage 1—study sample Total	WM	WF	BM	BF	Epiphysis study total	Measurement sample total	Stage 2—test sample Total	WM	WF	BM	BF	Stage 3—summary age sample total
0–9	8	1	0	1	6	33	22	13	1	3	4	5	0
10–19	12	0	1	5	6	45	27	24	2	6	7	9	4
20–29	9	0	2	3	4	227	1	22	4	3	6	9	20
30–39	10	0	2	6	2	—	—	43	10	15	8	10	35
40–49	10	4	0	6	0	—	—	38	13	9	10	6	27
50–59	9	5	0	3	1	—	—	18	5	5	6	2	11
60–69	10	5	0	4	1	—	—	16	7	4	3	2	3
70–79	6	4	1	1	0	—	—	7	1	1	3	2	0
80+	—	—	—	—	—	—	—	1	0	1	0	0	0
Total	74	*	*	*	*	305	50	182	43	47	47	45	100
Mean Age (years)	37.7	*	*	*	*	20.3	9.8	36.5	42.8	37.5	36.6	30.2	37.9
SD	21.7	*	*	*	*	7.0	5.9	18.1	15.0	18.2	19.7	17.5	10.7

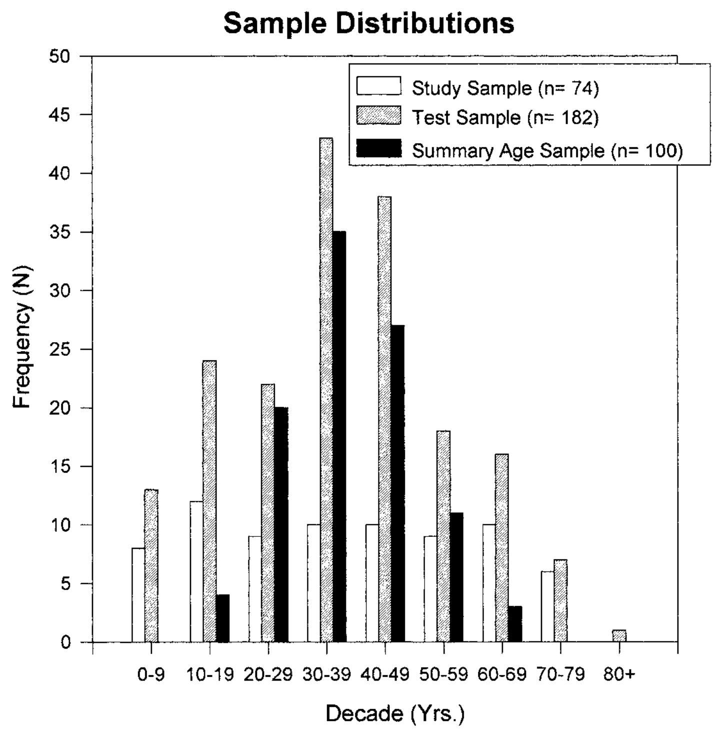


Fig. 1. Frequency and distribution of first rib specimens in phases 1, 2, and 3 of this study. Note that the mean age of the first two samples is quite similar [Study sample: mean (SD) = 37.7 years (21.7), range = 1–75 years; test sample: mean (SD) = 36.5 years (18.1), range = 1–80 years]. KS tests indicate that the means of these two samples were not significantly different while the distributions were markedly different.

texture, and the peripheral periarticular margin definitions of these structures. It is from this sample that the aging protocol was derived (Fig. 3).

Second, to determine whether preadult and adult ribs can be separated based on the fusion of the rib head's and tubercle's epiphyses and their subsequent remodeling, a larger sample of 305 preadult and young adult first ribs (aged 1–27 years) was selected from the Hamann-Todd collection (Table 1). It has been noted elsewhere that fusion of the rib head and its remodeling normally occurs by the 25th year (Williams and Warwick, 1980; White, 1991). Results in regard to the absence or presence of the rib head's and tubercle's epiphyses for specimens aged 12–27 years (n = 265) are found in Tables 2 and 3.

Third, to determine whether preadult ribs show increases in length and sternal face

TABLE 2. Frequency of rib head epiphyseal fusion

Age (years)	N	Unfused	Fusing	Completely fused
12	3	3	0	0
13	2	2	0	0
14	1	0	1	0
15	—	—	—	—
16	4	1	3	0
17	7	2	5	0
18	11	4	6	1
19	10	1	6	3
20	23	0	16	7
21	22	2	8	12
22	31	0	3	28
23	32	0	2	30
24	30	0	2	28
25	39	0	1	38
26	23	0	1	22
27	27	0	0	27

TABLE 3. Frequency of rib tubercle epiphyseal fusion

Age (years)	N	Unfused	Fusing	Completely fused
12	3	3	0	0
13	2	2	0	0
14	1	0	1	0
15	—	—	—	—
16	4	2	2	0
17	7	0	3	4
18	11	0	0	11
19	10	0	1	9
20	23	0	0	23
21	22	0	0	22
22	31	0	0	31
23	32	0	0	32
24	30	0	0	30
25	39	0	0	39
26	23	0	0	23
27	27	0	0	27

thickness with age, a sample of 50 preadults (aged 1–20 years) was drawn from the Hamann-Todd collection (Table 1). Barchilon and others (1996) have suggested that metric estimation of both the length and sternal face thickness is inappropriate beyond the second decade, and thus, this sample was truncated at individuals aged 20 years. Costal face thickness and rib shaft length of all preadult first ribs were measured using digital calipers (Fig. 2). Costal face thickness is the maximum superoinferior dimension of the costal face at its costochondral margin. Rib shaft length is the minimum distance between the midpoint of the tubercle facet and the anterior tip of the sternocostochondral margin. Based on these metric age indicators, age at death in preadult specimens can be computed using regression equations.

Stage 2: reliability of the first rib aging method

Stage 2 tested the reliability of the first rib aging protocol on a new sample of 182 age-verified preadult and adult first ribs (hereafter referred as the test sample) from the Hamann-Todd collection. The age structure of the test sample was constructed such that an unequal number of ribs appeared in each decade (Table 1, Fig. 1). The mean age of the test sample was 36.5 years (SD = 18.1, range = 1–80 years). To determine whether the test sample had an age structure different than the study sample, a two-sample Kolmogorov-Smirnov Test (KS) test was used. Since this test is sensitive to differences in the shape, dispersion, and skewness of data between two samples, a KS test with a p-value greater than 0.05 indicates that the two sample distributions are not significantly different from each other. The normal distribution of the test sample was not significantly different in mean age from the flat distribution of the Phase 1 study sample ($p > 0.05$).

The skeletal ages of the preadult sample were determined using both quantitative and qualitative observations. The adult sample was aged using qualitative characteristics only. One observer (CAK) aged the test sample [mean (SD) = 36.5 (18.1), range = 1–80, n = 182] on two different occasions (Obs1a and Obs1b, 3 months apart) and intraobserver reliability was calculated. Two observers (Obs2 and Obs3) independently aged the ribs while neither the population structure nor age range was revealed to them. Obs2 learned the technique independently by examining first a subset of preadult and adult ribs (n = 8) with revealed ages and extensive notes from CAK indicating key benchmark features. Obs2 then applied this technique to the test sample [mean (SD) = 36.5 (18.1), range = 1–80, n = 182]. Obs3 was provided with direct instruction on the technique by CAK. Obs3 examined only adult ribs [mean (SD) = 40.1 years (15.3), range = 17–80, n = 150]. Ages were estimated to the nearest whole year and

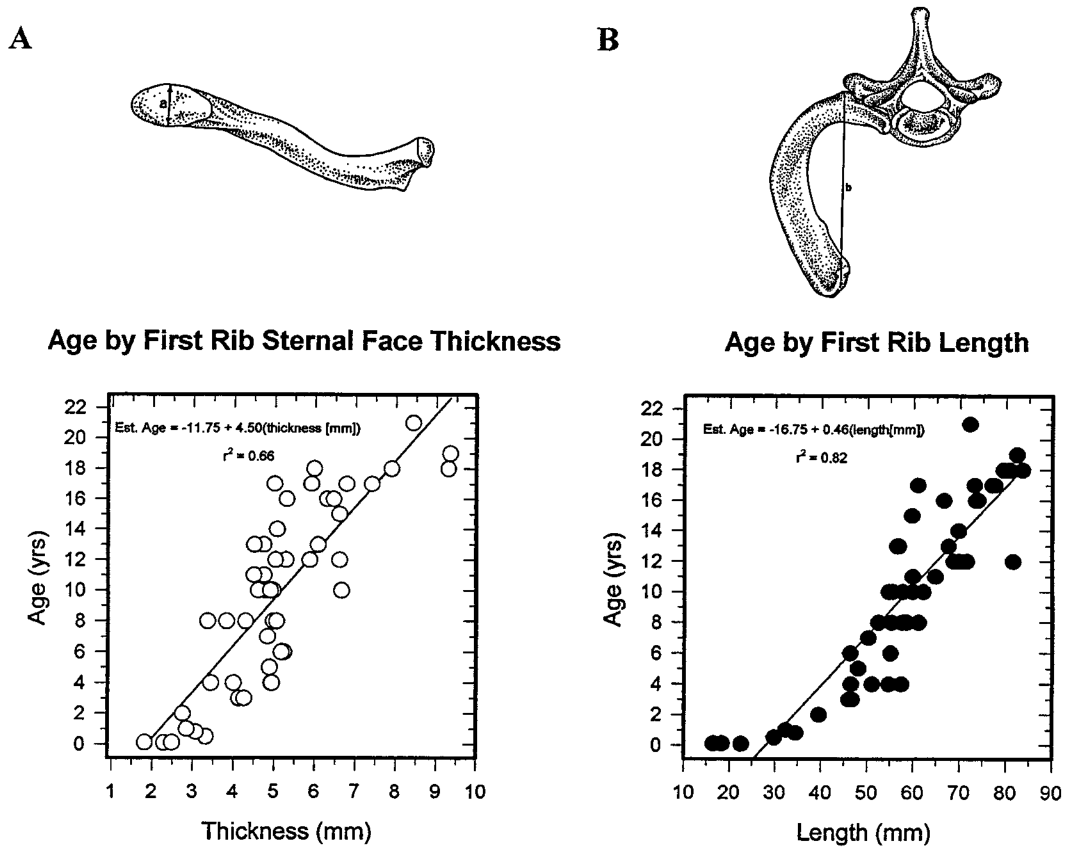


Fig. 2. Anatomy and mensuration of first ribs. A, Costal face thickness is the maximum superoinferior dimension of the costal face at its costochondral margin. B, Length is the minimum distance between the midpoint of the tubercle facet and the anterior tip of the sternocostochondral margin.

compared to chronological age. Interobserver reliability was calculated. Inaccuracy and bias were tabulated for each specimen and results were grouped by decade. Inaccuracy is the average error without regard to sign of error ($I = \Sigma|\text{estimated age} - \text{actual age}|/N$) and bias is the average error incorporating sign ($B = \Sigma\,[\text{estimated age} - \text{actual age}]/N$) (Lovejoy et al., 1985). The estimated and real age distributions were compared statistically using KS tests to demonstrate whether the actual age distribution of the test sample and that of the observer were significantly different (Lovejoy, 1971). A KS test with a p-value greater than 0.05 indicates that the two sample distributions are not significantly different from each other, and thus, the observed estimated age distribution could describe the actual age structure of the unknown sample.

Stage 3: comparison between first rib and other aging techniques

Stage 3 compared the first rib aging protocol with other established skeletal aging methods. One hundred age-verified individuals (hereafter referred to as summary age sample) from the Hamann-Todd collection (Fig. 1 and Table 1), previously aged by skeletal criteria [symphysis pubis, auricular surface, cranial suture, dental attrition, and trabecular involution of the proximal femur (Meindl et al., 1985; Lovejoy et al., 1985; Meindl and Lovejoy, 1985; Walker and Lovejoy, 1985)], were drawn separately to test the quality of the first rib aging method against

summary age. Estimated age for each indicator was provided generously by C. Owen Lovejoy and Richard Meindl (Kent State University, Kent, OH). The mean age of the summary age sample was 37.9 years (SD = 10.7, range = 18–66 years, n = 100).

The original multifactorial approach proposed by Lovejoy and co-workers (1985) estimated skeletal age using a weighted, mean summary age of multiple hard tissue age indicators. Weightings of the aging indicators were determined by correlation of individual age estimates with the first principal component representing skeletal age (Lovejoy et al., 1977, 1985). This study uses an unweighted mean summary age for comparative purposes of estimated ages. For this sample of 100 individuals, inaccuracies and biases were calculated for (a) first rib, (b) Lovejoy and coworkers' unweighted summary age, and (c) summary age including the first rib.

RESULTS

Stage 1A: age changes in preadult first ribs

Aging of the preadult first rib takes advantage of three phenomena: (1) appearance of secondary centers of ossification, (2) increase in size, and (3) change in morphology (See Fig. 3). Rib head epiphyseal fusion is an important criterion for the estimation of skeletal age. Incomplete fusion (unfused) refers to a secondary center of ossification that is either missing or separated by cartilage from the physeal plate. A fusing rib head epiphysis describes partial ossification of the physeal plate between the rib and the epiphysis. A completely fused secondary center of ossification describes an epiphysis that demonstrates a closed, remodeled physis. The fusion of the rib tubercle epiphysis is similarly described. As such, the appearance and fusion of secondary centers of ossification for the first rib provide an initial approximation of age range (Tables 2 and 3).

Age and fusion of rib head and tubercle. The appearance and fusion of the rib epiphysis divides the preadult group into three subset groups: (1) juveniles aged between birth and 13 years; (2) adolescents aged between 14 years and 20 years; and (3) young adults aged between 21 and 25 years (Table 2). Juveniles have an *unfused* rib head epiphysis. Adolescents tend to have an *incompletely fused* rib head epiphysis that retains evidence of an open physeal margin. Young adults tend to have a *completely fused* rib head epiphysis *with occasional regions of sharp physeal margins* (*contra* rounded margins of a remodeled physeal margin). Since these adults represent a morphologic transition from adolescent to more adult form, their morphology and subsequent aging will be discussed in Stage 1B.

The rib head epiphysis first appears as a calcified element in the Hamann-Todd collection (n = 305, range = 1–27 years) at about 14 years and continues to demonstrate an active ossification surface until the ages of 20–22 years (Table 2). The earliest age at which fusion was identified in the Hamann-Todd collection was 18 years, and the oldest individual with an unfused epiphysis was 21 years. Fusion of the epiphysis with the rib is a protracted process with an epiphyseal scar apparent until about 25 years. In the Hamann-Todd collection, the oldest individual with an incompletely remodeled epiphyseal scar was 28 years.

The rib tubercle facet epiphysis demonstrates a fusion pattern similar to the rib head epiphysis (Table 3). Both epiphyses begin the fusion process during the same year of life. The tubercle epiphysis fuses and remodels at an earlier age. The epiphysis begins fusing with the rib (n = 305, range = 1–27 years) at about 14 years and continues to demonstrate an active ossification surface until the ages of 17–19 years. The earliest age at which fusion was identified in the Hamann-Todd collection was 17 years, and the oldest individual with an unfused epiphysis was 19 years. Fusion of the epiphysis with the rib is a continuous process with a demonstrable epiphyseal margin with rounded edges apparent until about 21 years.

Age and first rib mensuration. During the first two decades, appositional growth of the costal end increases the thickness of the first rib sternal face producing a distended costal surface (Fig. 2A). This increase in

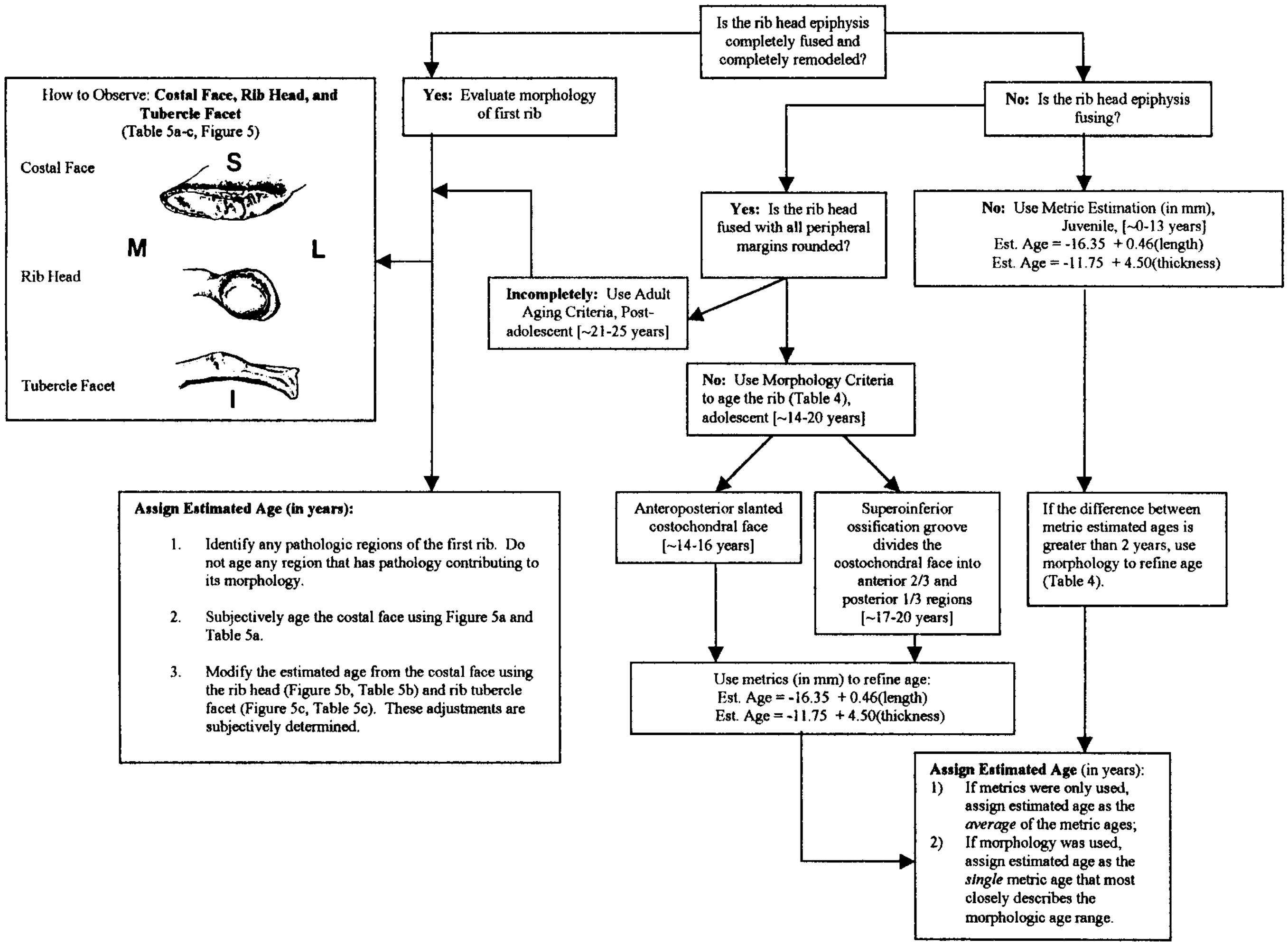


Fig. 3. First rib metamorphosis and aging protocol. (To be used in conjunction with Tables 4–8).

superoinferior thickness is highly correlated with age:

$$\text{Estimated age} = -11.75 + 4.50 \times \text{thickness (mm)}, \quad (r = 0.81, p < 0.01, n = 50). \tag{1}$$

Humans achieve their maximal thickness about age 20 and subsequent swelling is highly idiosyncratic. Therefore, this equation is not useful at a costal face thickness greater than 8 mm.

In addition, the rib increases in size and length through the first 20 years (Fig. 2B). Growth of the costal face and rib shaft increases the length of the rib with age and the following function has been found useful in estimating age:

$$\text{Estimated age} = -16.35 + 0.46 \times \text{length (mm)}, \quad (r = 0.91, p < 0.01, n = 50). \tag{2}$$

These regression equations can be used to estimate age in both juveniles and adolescents; however, cessation of first rib growth in size and irregular ossification of the sternocostochondral synchondrosis (Barchilon et al., 1996) limit metric assessment of chronological age after 20 years. Therefore, this equation is not useful for first ribs longer than 85 mm.

Age and morphology. The two most diagnostic morphologic criteria for aging the preadult first rib are: (1) the beginning of the anteroposterior slanted profile of the costal face which begins around age 12 (Table 4, Fig. 4, d and Fig. 3); and (2) the superoinferior ossification groove dividing the costal face into an anterior two-thirds and a posterior one-third regions between 17 and 20 years (Table 4, Fig. 4, e and Fig. 3). The first rib attains the adult form very early in life, but size, topography, texture, and margin appearance of the costal face vary considerably and consistently with age. At birth, the rib costal face demonstrates an ovoid shape, rounded margins, and a general surface texture of immature, smooth homogenous bone reminiscent of fine grain sand (Table 4 and Fig. 4, a). The rib head and tubercle share this morphology as well (Table 4 and Fig. 4, g, j). During the first 13 years of life, first ribs change rapidly in size and shape. Growth at the costal face produces an elliptical, bowed profile with central ridges projecting medially. Peripheral growth around the costal face exceeds that of the central core creating a rim. Growth in size at the rib head and tubercle surface parallels that of the costal face; however, morphologic changes are limited. Toward the end of the first decade, the rib head presents a more discoid appearance and the rib tubercle and its periarticular margins are even with the shaft profile (Table 4).

During adolescence (14–20 years), marked changes in the costal face and each secondary center of ossification occur. Different areas of the costal face demonstrate varying degrees of dynamic and relatively quiescent growth. During the transition from juvenile to adolescent morphology (13–15 years), more rapid growth of the anterior margins and surface in a medial direction creates an anteroposterior slanted profile to the face as well as an increase in margin definition (Table 4 and Fig. 4, d, f). Later in adolescence (17–20 years), the posterior third of the costal face accelerates its growth creating a superoinferior ossification groove (Table 4 and Fig. 4, e).

Both rib head and tubercle epiphyseal fusion begin about the 14th year and continue through the 20th year in the Hamann-Todd collection. As the rib head epiphysis fuses to the diaphysis, the margins of the physeal plate are initially distinct and sharp. Ossification proceeds variably throughout the physis, but it generally occurs central to peripheral in direction. Remodeling of the physeal plate produces rounded edges and margins. Like the rib head, fusion of the tubercle epiphysis follows a similar course of ossification pattern and appearance of the physeal margins. Fusion of the tubercle epiphysis also changes the profile of the tubercle by introducing a distended, lenticular contour, quite distinct from the elliptical profile seen earlier (Table 4 and Fig. 4, k, l, m).

Stage 1B: age changes in adult first ribs

Aging of the adult first rib takes advantage of three phenomena: (1) ossification of the costochondral interface, (2) remodeling of the ossified surfaces and peripheral mar-

TABLE 4. Preadult first rib morphosis[1]

Chronological age	Rib costal face		
	Geometric shape	General surface topography	General margin form
1	Anteroposterior ovoid	[a]Immature, smooth homogeneous bone	[b]Rounded, undefined
2			
3			
4	Elliptical with central surface projecting medially creating bowed appearance	Slight undulating ridges and depressions	
5			[c]Superoinferior bone deposition about margin creates rimmed appearance
6			
7			
8			
9			
10			
11		Ruffled, swollen immature bone	
12	[d]Anteroposterior slanted slanted face		Knobby margins with increasing definition
13			
14			
15			
16		Transverse ridges bounded by ovoid cavities	
17	[e]Superoinferior groove separating the face into an anterior two-thirds and a posterior one third		
18			
19			[f]Raised margins, defined
20			
Chronological age	**Rib head epiphyseal region**		
	Geometric shape	General surface topography	General margin form
1	Tear-drop	[g]Immature subchondral face	Distinct, rounded edge with rough inferior surface
2			
3			
4			
5			
6			
7			
8	Increasingly discoid		
9			
10			
11			
12	Circular		
13			
14			Sharp edges
15		[h]Epiphysis fusing	
16			
17			[i]Rounded, worn edges
18			
19			
20			
Chronological age	**Rib tubercle epiphyseal region**		
	Geometric shape	General surface topography	General margin form
1	Ellipsoid	[j]Immature, crescent profile when viewed from superior	Rounded
2			
3			
4			
5			
6	Ellipsoid with defined articular surface		
7			
8			
9			
10			
11			
12			
13			
14	[k]Ovate, robust profile that swells beyond shaft profile		Defined, sharp edges
15			
16		[l]Epiphysis fusing	
17			
18			
19		Smooth articular surface	
20	Lenticular contour		[m]Rounded edges

[1] Superscript letters denote major landmarks in first rib morphosis.

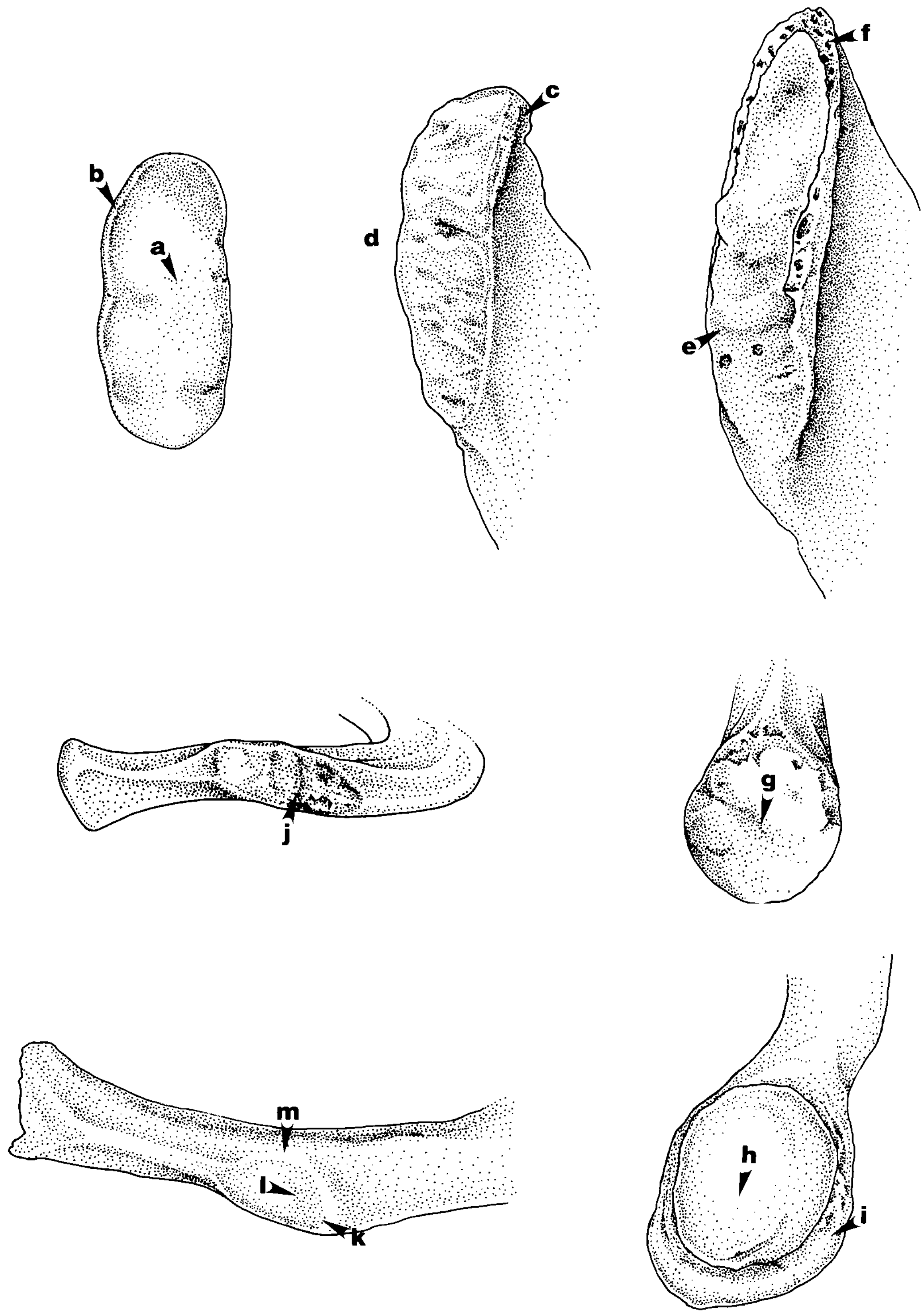


Fig. 4. Illustrative features for preadult first rib morphogenesis.

TABLE 5. First rib morphosis—Costal face[1]

Chronological age	Geometric shape	Surface topography	Surface texture	Margins of face	Periarticular margins
20		Knobby, superoinferior ridges	Texture is even, unremarkable		Smooth and unremarkable
21				Interior and exterior margins are rounded	
22					
23	Superoinferior shape of face increases thickness, flaring profile				
24		Surface becomes flat, knobby topography is lost			
25			Increasing filamentous subchondral ossification	Interior margins are rounded and exterior margins are angled	
26					
27	[a]Ovate, anterior thickening of margin projects medially				
28					
29		Pittings in surface are evident		Rounded, distinct thin profile except for anterior thickening	
30			[b]Cribriform texture		
31					
32					
33		Ridges of cortical bone creates distinct macroporosities			
34					
35			Irregular small pits with smooth margins		Superior margin projecting and becoming increasingly rugose
36	[c]Ovate, anteroposterior bone deposition creates superior projection medially				
37		Increasing excavation of surface topography			
38				Margins begin projecting	
39					
40	[d]Ovoid profile, cartilage encapsulated by shell of cortical bone creating a central concave cavity			[d]Thin shell transforms into local thickening of margin with anterior margin extended greater than posterior, "scalloped edges"	
41					
42					
43					
44					
45			Exostoses forming		Rugosity extends from margin with irregular exostoses
46					
47					
48	Ovoid profile, U-shaped cavity deepens as shell expands from sternal face	[e]Occasional irregular osteophytic spikes emmanating from surface projecting medially			
49			Increasing number of pits with angular margins, occasional "honeycombed" appearance		Region of the costoclavicular ligament increases in rugosity
50					
51					
52					
53					
54	Circular profile, expansion of U-shaped shell creates rugged superior rib shaft about face				
55					Superior periarticular surface projects greater than inferior surface
56					
57					
58					
59					
60	Irregularly shaped, hollowed shell for cartilage becoming increasingly pronounced			[f]Margins become rugged, irregular striations along shaft, and swollen knobby projections	
61					Highly irregular with poorly organized bone
62					
63		Surface becomes rugged and irregular			
64					
65					
66					
67					
68					
69				Anterosuperior surface and margin increase prominence	
70					
71			Increased senescence of surface texture increases rugostiy		
72					
73	[g]Filled cortical cavity				
74					
75					
76		Surface irregularities contribute to filled cortical cavity			
77					
78					
79					
80					

[1] Superscript letters denote major landmarks in first rib morphosis.

gins, and (3) degenerative changes of ossified surfaces and peripheral margins (see Fig. 3). Information regarding chronological age can be obtained from the sequential ossification pattern of the sternocostochondral joint (see also Michelson, 1934; Hass, 1943; Dearden et al., 1974) and from morphologic changes at the rib head and tubercle (Tables 5–7; Figs. 5A–C). Adults are defined here based on complete fusion of the rib head epiphysis.

TABLE 6. First rib morphosis—Rib head[1]

Chronological age	Shape of head	Surface topography	Surface texture	Margins of rib head	Periarticular margins
20	Circular profile of head	Convex surface	[a]Fused remodeled epiphysis, smooth articular surface	[b]Rounded	Smooth
21					
22					
23					
24		Beginning of surface irregularities		Dorsal outer margin becomes continuous with neck	
25					
26					
27					
28	Local rugosities occur			Anterior superoinferior margin becomes angular	
29			Smooth articular surface		
30					
31					
32					
33					Initial irregularities especially in anterior margin
34					
35					
36					
37					
38		Begin formation of mediolateral groove due to build-up of superior margin		[d]Rim becoming defined with marginal irregularities and ridges	
39					
40	[c]Circular with increasing robusticity and convex profile		Continued smooth articular surface		
41					
42					
43					
44				Rim well defined and sharply angled	
45			Local densification of articular surface		
46					
47					
48				[e]Irregular, distended surface and edges with prearticular groove	
49					
50			[f]Smooth with occasional pits or depressions, macroporosity locally		
51	Ovoid, irregular concentrically layered profile				
52					
53					
54				Exostoses form	
55					Inferior margins increase in irregularity
56					
57					
58					
59					
60					
61		Secondary flattening of surface topography			
62					
63					
64					
65			Rugose profile with macroporosity often		
66					
67					
68					
69					
70	[g]Irregular geometry with inflated puffy pockets of bone				
71					
72					
73					
74					
75			[h]Gross pitting of articular surface		
76					
77					
78					
79					
80					

[1] Superscript letters denote major landmarks in first rib morphosis.

TABLE 7. First rib morphosis—tubercle facet[1]

Chronological age	Shape of tubercle and neck	Surface topography	Surface texture	Margins of facet	Periarticular margins
20	[a]Lenticular profile		Dense, smooth texture		
21		Superoinferior topography is rounded			[b]Margins are smooth and rounded
22			Cortical bone with depressions and ridges		
23					
24	Ovate, swollen appearing outline when compared to shaft			Medial margin becomes angular, raised and distinct	
25					
26					
27			Smooth cortical surface		
28					Begins showing elevation due to superior ligamentous attachment of joint capsule
29					
30	[c]Distinct cresting of neck along costotransverse ligament with defined ridges	Topography becomes flatter than previous			
31					
32					
33					
34					
35					
36	Epiphyseal billowing associated with periarticular bone deposition				Begins showing rugosity
37					
38				[d]Superior margin becomes angular	
39					
40			Pitting may develop on tubercle facet		
41				[e]Inferior margin rounded and indistinct, other margins become increasingly worn	
42					
43	[f]Tear-drop shape with pointed medial margin				
44					
45					Superior marginal deposition increases with surface rugosity
46					
47					
48					
49			Lipping begins on inferior margin		
50		Beginning of mediolateral concavity		[h]Beginnings of irregularities with osteophytes	
51					
52					Osteophytic formations become prominent
53			[g]Rib surface becomes slightly rugose		
54	[g]Ovate, crescent shaped swelling along superior edge				
55					
56					
57					
58					
59					
60				[i]Margins become swollen and irregular	
61					
62	Irregular, circular profile				
63		Macroporosity develops, but not exclusively			
64					
65					
66				Increased marginal pitting within rim	
67					
68					
69					
70			[j]Pitting increases in severity altering surface texture		
71					
72					
73				Irregular profile	
74					
75					
76					
77					
78					
79					
80					

[1] Superscript letters denote major landmarks in first rib morphosis.

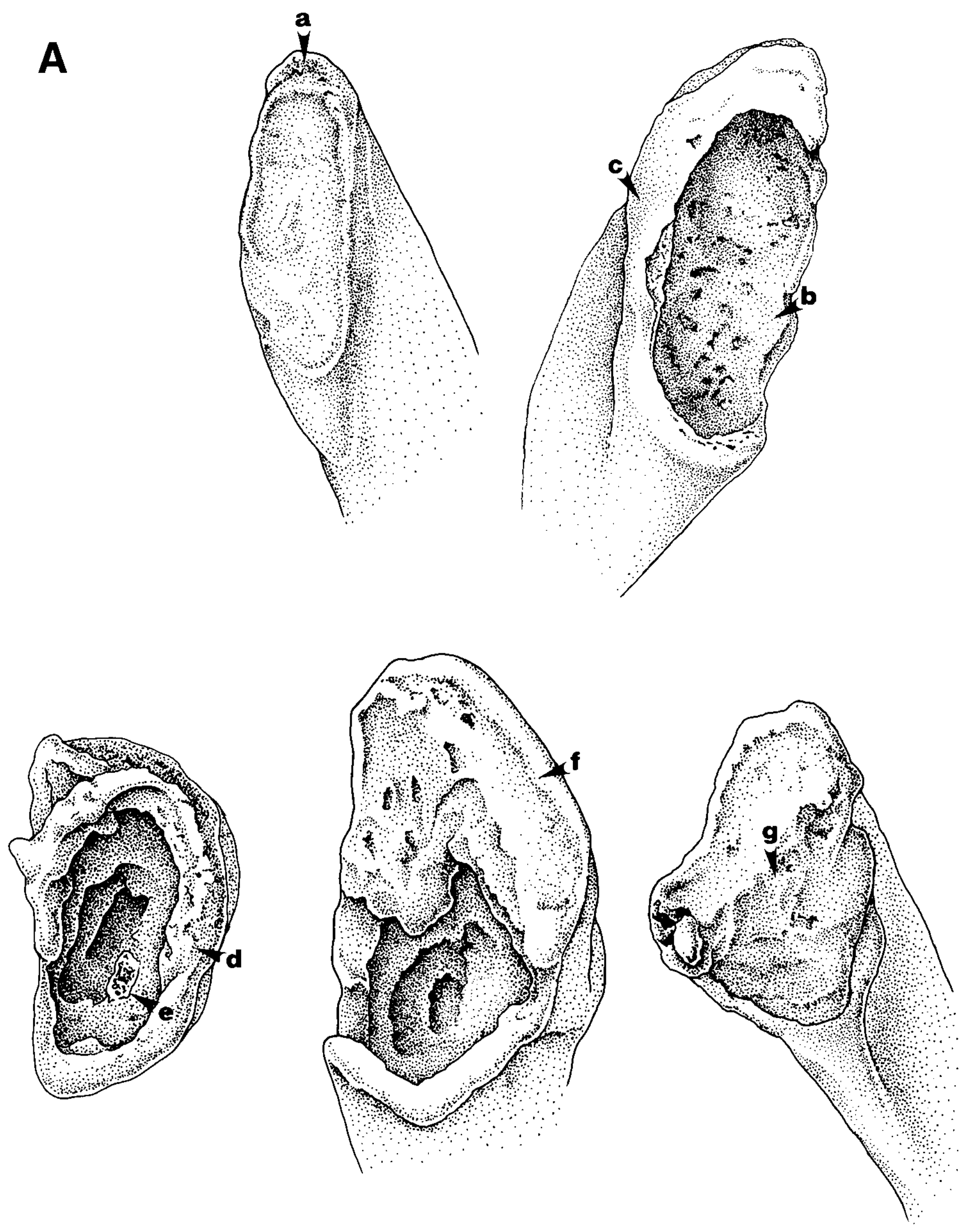


Fig. 5. (**A**) Illustrative features for adult first rib costal face morphogenesis. (**B**) Illustrative features for adult first rib head morphogenesis. (**C**) Illustrative features for adult first rib tubercle morphogenesis.

Costal face

Cessation of growth during the terminal stages of adolescence has created a flat superoinferior profile at the costal face. The young adult (21–25 years) first rib costal face shows little evidence of morphological change during this period. The surface texture initially is smooth with undulating ridges occasionally present. The peripheral margins are also smooth and rounded (Table 5 and Fig. 5A) (see also Michelson, 1934, Fig. 2–7).

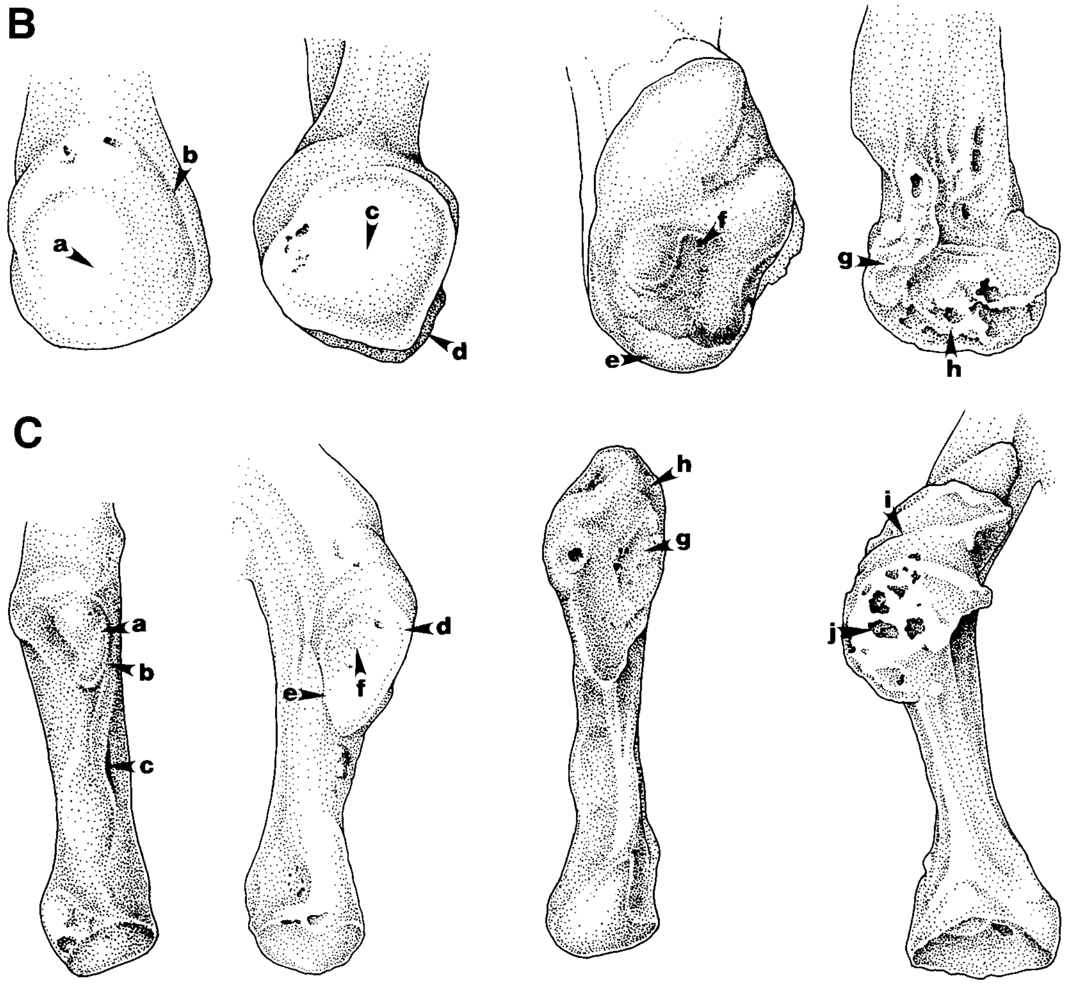


Fig. 5.

The costal cartilage begins to ossify at the costal face and proceeds to the sternum (Michelson, 1934). Ossification and remodeling of this cartilage begins about the age of 26 years and continues at least until the eighth decade. The first evidence for the costochondral ossification in the early adult (26–30 years) is the formation of an osseous beak along the superoanterior margin that projects medially (Table 5, Fig. a in Fig. 5A) (see also Michelson, 1934, Fig. 2–10). Increased filamentous subchondral ossification of the costal surface creates a cribriform surface texture. The advanced ossification of the superior marginal cartilage adds to the osseous beak and creates a rugose marginal profile. These changes are characteristic of the fourth decade (Table 5 and d and e in Fig. 5A). Changes during the fifth decade include the introduction of small irregular exostoses along the costal surface and peripherally along the margins as a consequence of continued ossification. A U-shaped central cavity forms secondarily from continued peripheral ossification. This cavity increases in depth with age, but shows considerable variation from individual to individual (Table 5 and f in Fig. 5A). Ossification and remodeling of the costochondral cartilage slows during the latter half of the fifth decade (47–50

years) and throughout the sixth and seventh decade. During this period, the costal surface and the peripheral margins becomes more rugged and irregular in appearance (Table 5). Senescence (70+ years) and degenerative changes in the costochondral surface bring an increasingly filled central cavity and a spherical, globular surface texture (Table 5, and g in Fig. 5A).

TABLE 8. Intraobserver and interobserver reliability

Pairing	N	Mean difference (SD)	Range (min, max)
Obs1a-Obs1b	182	−0.3 [4.9]	33 years [−20, 13]
Obs1-Obs2	182	−0.3 [8.3]	63 years [−27, 36]
Obs1-Obs3	150	2.4 [7.1]	43 years [−19, 24]
Obs2-Obs3	150	3.2 [9.1]	60 years [−22, 38]

Rib head

The young adult (21–25) rib head represents a morphologic transition from the incompletely fused, adolescent rib head to a completely fused, remodeled adult rib head. As seen in adolescents, the rib head epiphysis begins with a central ossification connection that shows increased peripheral ossification with age. Rounded margins at the periphery of the rib head signify the end-stages of rib head remodeling by the end of the third decade. The occasional open physeal margin in conjunction with rounded, peripheral margins elsewhere denote the uniqueness of the young adult rib head. The open physeal margins close and remodel completing the fusion of the rib head epiphysis signaling the transition to the adult rib head.

The adult rib head initially exhibits a circular profile with a smooth texture and rounded peripheral margins (Table 6, and a and b in Fig. 5B). Early changes in the rib head articular surface include the formation of small bony ridges crossing the articular surface. Marginal irregularities especially along the anterior rim are evident during the fourth and fifth decades (30–50 years) (Table 6 and c and d in Fig. 5B). Occasional porosity of the rib head surface and exostoses along the margins appear during the sixth decade (50–60 years) (Table 6 and f in Fig. 5B). The seventh and eighth decades (60–80 years) are characterized by a highly porous articular surface with marginal lipping and exostosis (g and h in Fig. 5B).

Tubercle facet

After fusion of the tubercle epiphysis [typically during the latter stages of adolescence (17–20 years)], the surface texture of the facet is smooth and the peripheral margins are rounded. Beginning in the late third decade (26–30 years), the costotransverse ligament attachment produces marked beveled ridges on the posterior aspect of the neck (Table 7 and c in Fig. 5C). Periarticular billowing and marginal rugosity are evident in the fourth decade (d and e in Fig. 5C). Osseous lipping in the form of a crescent forms along the superior edge of the facet while osteophytic irregularities become apparent along the periarticular margins. The surface texture presents lipping and a mediolateral concavity during the fifth and sixth decades (g and h in Fig. 5C). Erosive changes (pitting) associated with developed lipping and exostosis are evident at the tubercle facet during the sixth and seventh decades (i and j in Fig. 5C).

Stage 2: reliability of first rib aging protocol

Intraobserver reliability. Obs1 estimated the age of 182 age-verified juvenile and adult ribs on two occasions separated by three months. Intraobserver reliability was high (Table 8, Fig. 6). The mean difference between observations was to underage specimens by 0.3 years [SD = 4.9; range = 33 years (13 to −20 years)]. Inaccuracies and biases of estimated versus real age in the two analyses were also very similar (Obs1a: Inacc = 4.5 years, Bias = overage by 2.5 years; Obs1b: Inacc = 4.6 years, Bias = overage by 2.2 years). KS tests indicate that each distribution of estimated ages did not differ significantly from either each other or from the real chronological age distribution ($p > 0.05$).

Interobserver reliability. There is strong consistency between observers in age estimates (Table 8, Fig. 6). A summary statistic

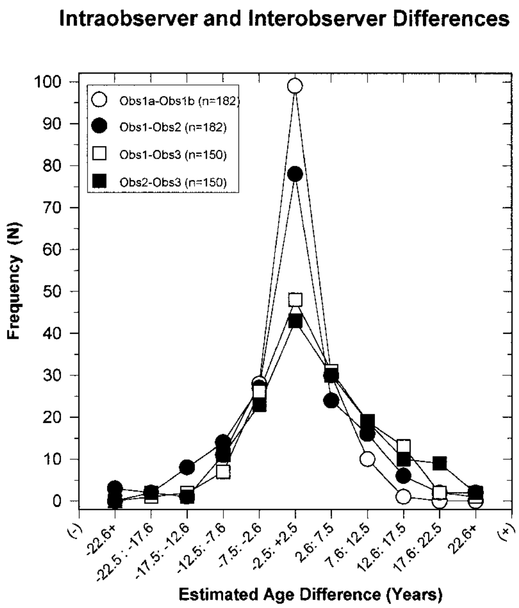


Fig. 6. Intraobserver and interobserver reliability for the first rib method. Frequencies of the difference in ages between different observers are grouped in lustra. Positive differences are plotted to the right and negative differences are plotted to the left. Intraobserver differences are plotted as open circles (Obs1a–Obs1b). Interobserver differences are plotted as the difference between various observers (Obs1–Obs2; Obs1–Obs3; Obs2–Obs3). Note that the general tendency to either overage or underage individuals clusters between ±7.5 years.

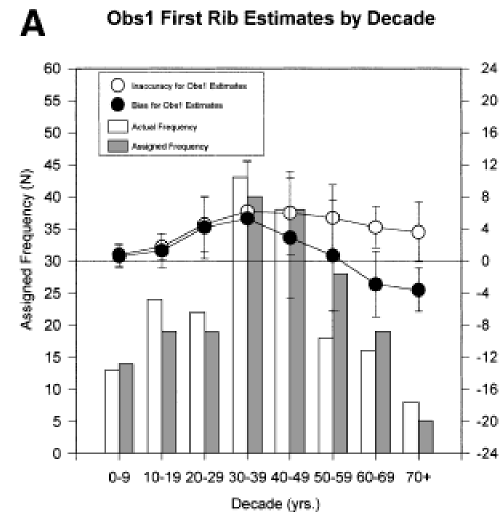
describing the mean difference between one observer's age-at-death assessment and another's can be calculated (e.g., Difference = Obs1 age − Obs2 age). When calculated in this manner, mean ages were not significantly different between the different observers, although estimates of an individual specimen's age could be markedly different. KS tests indicate that each observer's distribution of estimated ages did not differ significantly from the distribution of real chronological age ($p > 0.05$).

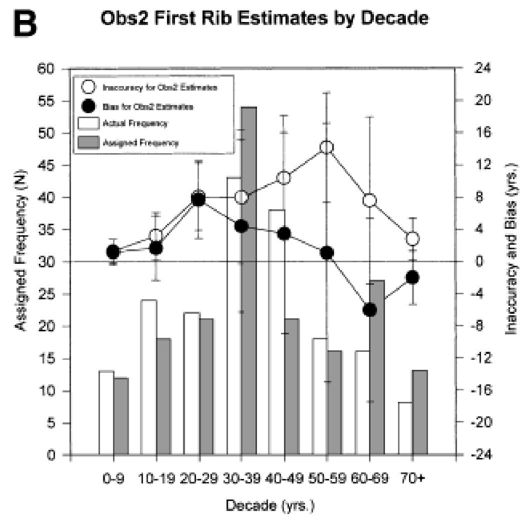
Inaccuracy and bias of first rib aging method. Inaccuracies and biases of the first rib method by decade appear in Figures 7A–C. All observers tended to overage ribs before the sixth decade whereas the tendency became to underage ribs during and beyond the sixth decade. The frequency distribution for each observer is also indicated (Figs. 7A–C). In each case, the number of individuals assigned to a particular estimated age range closely reflects the true distribution of specimens. KS tests indicate that each observers' distribution of estimated ages did not differ significantly from the distribution of real chronological age ($p > 0.05$).

Sex and race differences in aging. Inaccuracies and biases of the first rib method as a function of recorded sex and race origin are presented in Table 9. Observers estimated age of first ribs in the same magnitude and direction independent of sex or race origin (Table 9). The difference between estimated age and real age for each sex and race is comparable within each observers' subset of estimated ages. In only one instance (Obs3: White and Black) does the tendency to overage (+) and underage (−) differ. KS tests indicate that each observer's distribution of estimated ages did not differ significantly based on sex or race differences nor did they differ from the distribution of real chronological age ($p > 0.05$).

Stage 3: comparisons with other aging techniques

Alone, the first rib method has an accuracy approaching that of a multifactorial approach and presents a similar pattern of bias (Table 10, Figs. 8A–C). CAK examined the first ribs from 97 individuals for which a nonweighted, mean summary age (MSA) had already been computed using estimated ages for the symphysis pubis, auricular surface of the ilium, cranial sutures, dental attrition, and trabecular involution of the proximal femur (estimates generously provided by C.O. Lovejoy and R.S. Meindl). The mean difference between CAK and MSA observations was 0.4 years [SD = 6.6; range = 36.1 years (−15.1 to 21 years)]. Inaccuracies and biases of estimated versus real age in the two analyses were also very similar (CAK: Inacc = 4.8 years, bias = overage by 1.5 years; MSA: Inacc = 4.6 years, bias = overage by 1.1 years). Sample means were not significantly different between CAK and MSA, although estimates of





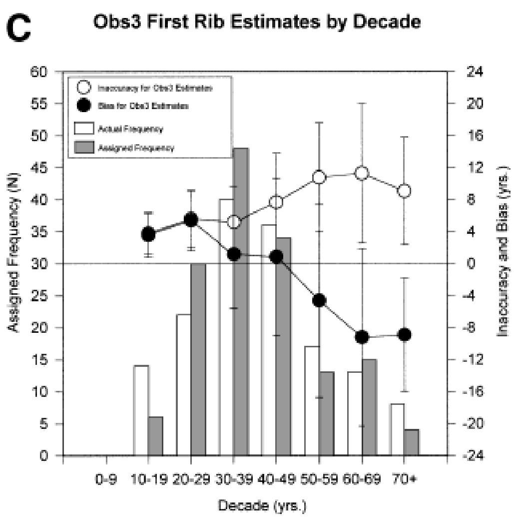


Fig. 7. Inaccuracy and bias of the first rib method. (**A**) Obs1, (**B**) Obs2, (**C**) Obs3 first rib estimates by decade. Inaccuracies and biases were tabulated for each specimen and grouped by decade. Data are plotted as the mean and standard deviation by decade for each of the observers. Open circles represent the observers' inaccuracy while the closed circles represent bias per decade. Bar graphs represent actual and assigned frequencies by decade for each of the observers.

TABLE 9. Inaccuracy (I) and bias (B) of the first rib as a function of sex and race

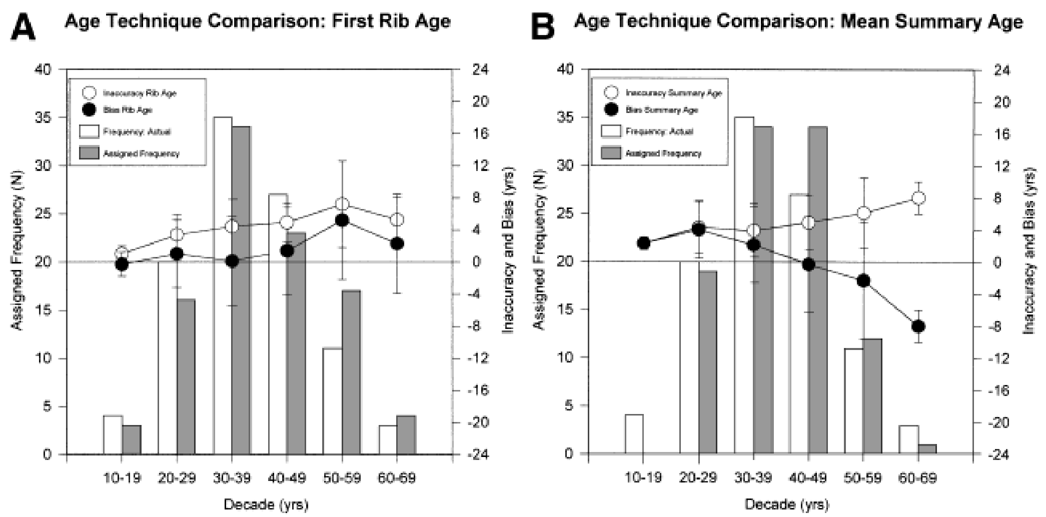
	Obs1 (n = 182)			Obs2 (n = 182)			Obs3 (n = 150)		
	N	Mean (yrs)	SD	*N*	Mean (yrs)	SD	*N*	Mean (yrs)	SD
Whites (I)	90	4.7	4.6	90	7.6	6.7	77	7.1	5.7
(B)		−1.8	6.3		−0.6	10.1		1.9	8.9
Blacks (I)	92	4.6	4.9	92	7.9	8.4	73	7.0	6.2
(B)		−2.6	6.2		−4.4	10.6		−1.7	9.3
Males (I)	89	4.9	4.5	89	7.3	6.8	76	6.9	5.9
(B)		−2.2	6.2		−2.0	9.8		0.3	9.1
Females (I)	93	4.4	5.0	93	8.2	11.3	74	7.3	6.0
(B)		−2.3	6.3		−3.0	5.0		0.0	9.4

individual estimated age could be markedly different (up to 21 years different). KS tests indicate that each distribution of estimated ages did not differ significantly from either each other or real chronological age ($p > 0.05$).

Can the first rib aging standard improve the quality of a multifactorial age estima-

TABLE 10. Inaccuracy (I) and bias (B) of select aging methods as a function of sex and race

	First rib (n = 97)			Non-weighted summary age (n = 100)			Non-weighted, rib summary age (n = 97)		
	N	Mean (yrs)	SD	N	Mean (yrs)	SD	N	Mean (yrs)	SD
Whites (I)	29	5.6	3.1	29	5.6	3.6	29	5.0	3.1
(B)		0.2	6.5		1.0	6.6		0.8	5.9
Blacks (I)	68	4.4	3.9	71	4.2	3.3	68	4.0	3.1
(B)		2.1	5.5		1.1	5.2		1.3	4.9
Males (I)	58	4.9	2.8	61	4.3	3.4	58	4.1	3.1
(B)		2.2	5.2		1.7	5.2		1.8	4.8
Females (I)	39	4.6	4.6	39	5.0	3.5	39	4.6	3.2
(B)		0.5	6.6		0.1	6.2		0.2	5.7



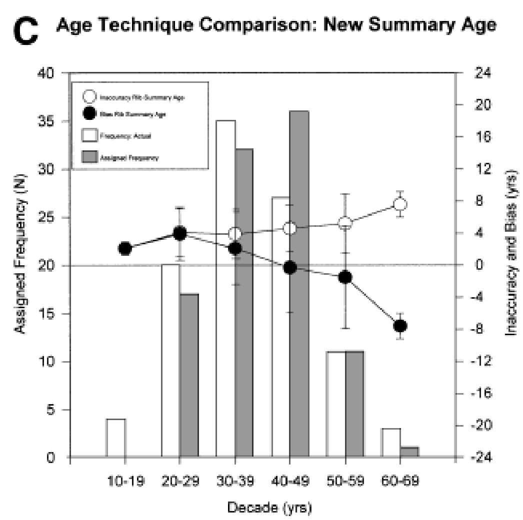


Fig. 8. Inaccuracy and bias of the first rib method (**A**) mean summary age (**B**) and mean summary age with the first rib (**C**). Inaccuracy and bias are defined as in Fig. 7. Data are plotted as the mean and standard deviation by decade for each of the methods. Open circles represent each method's inaccuracy while the closed circles represent bias per decade. Bar graphs represent the actual and assigned frequencies for each of the methods.

tion? As shown above, age-at-death estimation using the first rib compares favorably with a multifactorial approach. When mean summary ages are computed in conjunction with the first rib, the mean difference between the new summary age (NMSA) and the original mean summary age (MSA) was 0.1 years [SD = 1.2; range = 7.8 years (−2.5

to 5.3 years)]. Inaccuracies and biases of estimated versus real age in the two analyses were also very similar (MSA: Inacc = 4.6 years, bias = overage by 1.1 years; NMSA: Inacc = 4.3 years, bias = overage by 1.2 years). KS tests suggest that each distribution of estimated ages (MSA or NMSA) did not differ significantly from chronological age ($p > 0.05$).

Inaccuracies and biases of the first rib, multifactorial, and multifactorial plus first rib methods as a function of recorded sex and race origin are presented in Table 10. Each approach tends to overage ribs in a similar magnitude and direction independent of sex or race (Table 10). The inaccuracy within each sex and race subgroup is comparable, differing at most by 1.4 years. In each instance, the addition of the first rib improves the mean summary age estimate (Table 10).

DISCUSSION

Skeletal age indicators depend on the relationship between morphologic change and age, the distinctiveness of morphologic metamorphosis, and the ability to identify and assess these changes consistently both within and between observers. The first rib aging standard meets these requirements. First, the first rib shows a strong relationship between predictable morphologic change and chronological age. Second, it presents distinct anatomical attributes that can be used to estimate age. Third, there is a strong relationship between intraobserver and interobserver first rib age estimates.

The anatomy of the first rib is dynamic with no discrete, clearly defined phases (See also Kampen et al., 1995). This technique describes continuous morphologic change in three regions of the first rib allowing great flexibility in aging. Significant latitude in the assignment of age to a single region of the rib allows one to combine all of the available age information into a subjective, single estimated age. The true power of the first rib aging technique rests in its ability to continuously evaluate changing first rib morphology at multiple sites and synergistically combine all available information into a single, reliable age estimate. Flexibility in assigning an estimated age at each of three distinct morphologic areas provides the investigator considerable latitude in assigning a specified estimated age and thus avoid "lumping" of specimens into age categories. Such an approach also provides an internal check of the final estimated age since each region of the rib servers as a independent marker for age at death. This robust aging standard satisfactorily ages single individuals or populations and therefore can be useful in a wide variety of disciplines such as forensic medicine or paleodemography.

To use this technique effectively, several qualitative factors must be considered. First, when aging preadult first ribs, metric assessment of rib length and costal face thickness are the most accurate measures of skeletal age. Age discrepancies of more than 2 years between computed ages can be resolved with information gained from a subjective morphologic analysis of the costal face, rib head, and tubercle facet. Second, experience suggests that when aging adult first ribs, the costal face, rib head, and tubercle facet contribute more meaningful information at different times. The costal face is the most sensitive skeletal age marker and reasonably describes skeletal age throughout the entire lifespan. The rib head and tubercle facet contribute significant information about skeletal age during the sixth through eighth decades when the pattern of costal face ossification, remodeling, and senescence becomes erratic.

In summary, aging the first rib is simple and reliable. Its accuracy is very similar to the multifactorial approach proposed by Lovejoy, Meindl, and co-workers (1985a). It has been shown to be a robust indicator of age when used alone. When the first rib is incorporated into a multifactorial aging approach, it improves the quality of the age estimate. The easy identification of the first rib and its subsequent reliability in aging make the proposed aging method and standard highly applicable for forensic and physical anthropologists.

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